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Tests on superconducting helix resonators

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A niobium helix-resonator cavity close to the frequency suitable for a heavy-ion accelerator has been subject to an 8-week test, including 323 h at full power (axial electric field $E_{ax} > 2.5$ MV/m). The cavity, with an anodically deposited protective film of Nb_2O_5, had a high Q and supported high fields without deterioration over the whole period during which it was subject to a moderate internally generated x-ray dose. Properties were found to be stable against considerable thermal cycling and exposure to air. Measurement of emitted x-ray maximum energy allowed an independent corroboration of the field measurement calibration.

The cost of a heavy-ion accelerator system that includes a linear accelerator can be considerably reduced if the latter is made superconducting. Until recently, results with niobium resonators were discouraging, since both surface resistance and attainable accelerating fields deteriorated with use,[1] presumably through changes in the niobium surface. An important breakthrough was the discovery[2] that an anodically deposited Nb_2O_5 layer could protect the surface and stabilize both the low rf surface resistivity and the high attainable fields in a 10-GHz cavity. Work at Karlsruhe[3] and at Argonne (reported here) has shown that this technique is equally effective with the lower-frequency helix cavities proposed for use in a heavy-ion accelerator.

Despite the evident protection offered by the oxide, the suitability of a superconducting resonator structure for use in an accelerator was still in doubt because model tests were typically short runs, providing no assurance that resonators would sustain high electric fields over long periods. To check this point, an anodized helix cavity was given an extended 8-week test at Argonne National Laboratory at high power (axial electric field $E_{ax} > 2.5$ MV/m).[4] This field is comfortably above the value 2 MV/m, which is suitable for the design of a heavy-ion post accelerator. No deterioration of maximum attainable field or Q was observed; indeed, the high-field Q values actually improved with time. The calculated field values were corroborated by energy measurement of emitted x rays.

Two resonators, A and B, were tested (Fig. 1) at a pressure of $<10^{-8}$ Torr. Power runs were at 1.8 K where helium superfluidity allowed heat transfer with zero mass flow. Helix B, originally intended only for fabrication practice, was electropolished,[5] and anodically oxidized[6] in 0.2N H_2SO_4, giving 310 Å of Nb_2O_5. It was left exposed to air for 5 months prior to test. Helix A was chemically etched, heated (1850 °C) in the Stanford HEPL furnace,[7] and returned in a nitrogen atmosphere. It was then electropolished and anodized with a 400-Å oxide layer.

The quantities of interest were Q_{00} (low-power cavity Q_0) as a measure of surface resistivity, Q_{0p} (powered cavity Q_0) whose difference from Q_{00} is a measure of field-dependent losses, and maximum E_{ax} attainable. Q_{00} was measured by the decay method. Using the fact that the

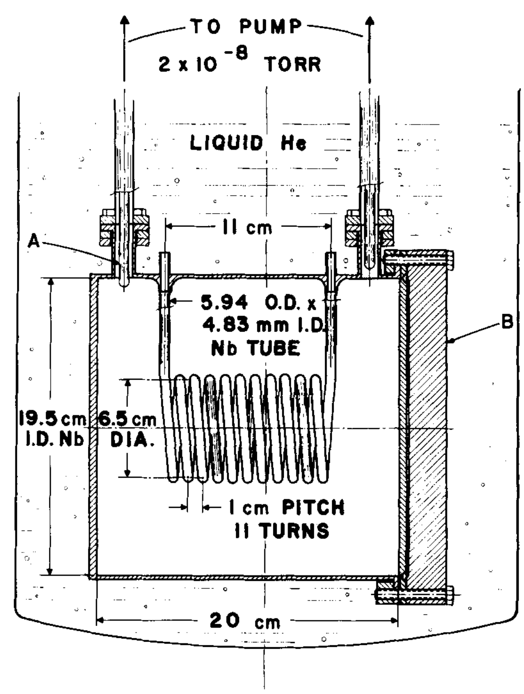

FIG. 1. Helix A and helix B structure: A, adjustable rf probes (one probe used as rf feed, the other as detector); B, titanium stiffening plate. Ratio of can diameter to helix diameter is 3.0. Liquid helium bath surrounds the cylinder. Heat is carried away with no mass transfer through the superfluidity of helium at 1.8 K.

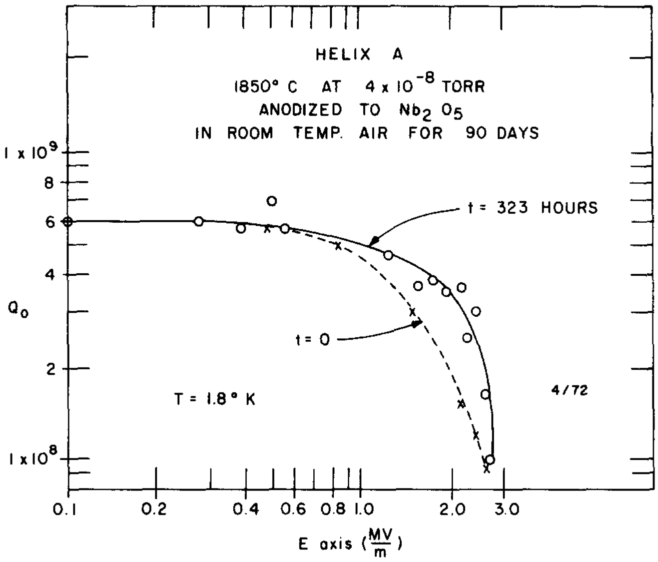

FIG. 2. Q_0 versus rf power level measured by frequency shift Δf and related as $E_{ax} = 0.125(\Delta f)^{1/2}$. The Q_0 drop is due to energy consumption by cold-emission electrons in an intense field at the helix ($E_{max} = 9.4E_{ax}$), which shows up as brehmstrahlung x rays of maximum energy close to $0.092E_{ax}$.

frequency decreases with increasing rf field intensity, Q_{0p} was derived from the experimentally determined relation $PQ_{0p} = 24.6 \times 10^4 \Delta f$, with P (W) as the net dissipation and Δf (kHz) as the frequency shift. Combining with a theoretical (E_{ax}, PQ) relation, the equation E_{ax} (MV/m) $= 0.125(\Delta f)^{1/2}$ was used for the axial field. The maximum fields on the helix surface were given by E_{max} (MV/m) $= 9.4E_{ax}$ and B_{max} (G) $= 280E_{ax}$.

For 6 weeks following anodization, helix A suffered considerable handling because of vacuum seal problems. The first test yielded $Q_{00} = 1.1 \times 10^9$. With the application of the first- and third-mode driving frequencies and probcessing, the multipactoring barrier was overcome. (The cavity operated in the first, or fundamental, mode at 96.9 MHz.) Q_{00} then dropped to 6×10^8, but thereafter remained constant at this value. Values of $E_{ax} = 2.7$ MV/m were measured over extended periods. During a period of $2\frac{1}{2}$ months, the resonator was warmed and cooled eight times, with several exposures of air, suffering no deterioration of Q_0 or attainable field.

After thermal cycle testing, it was left in air for 2 months prior to the long test run, in which it was kept cold continuously with high fields ($E_{ax} > 2.5$ MV/m) for a total of 323 h of powered run. Figure 2 shows Q_0 vs E_{ax} at the beginning and end of the run. The x-ray output curves (measured with an ionization chamber) showed a sharp drop corresponding to the rise in Q_0 at high field; we interpret this to mean that continuous running caused a decrease in electron emission.

The maximum brehmstrahlung x-ray energy vs Δf was measured with a calibrated NaI(Tl) scintillation detector outside the cryostat, checking within 5% the E_{ax} calibration factor. Measured x-ray external intensities were a very poor measure of intensities within the cavity because of enormous absorption by cavity wall and cryostat. Quantitative relative intensities for use in a Fowler-Nordheim plot were completely unreliable because of very large changes of x-ray absorption with E_{ax}.

Helix B was constructed with less care and had no thermal treatment; nevertheless, it yielded low power $Q_{00} = 3 \times 10^8$ and maximum $E_{ax} = 1.5$ MV/m at $Q_{0p} = 1 \times 10^8$. It, too, was exposed to air for months after anodizing and prior to test. No deterioration resulted from repeated warming to room temperature.

Probably the single largest uncertainty in the usefulness of this structure for a linear accelerator seems to be allayed. The Nb_2O_5 surface stabilizes the surface against attack from the atmosphere and allows stable and conservative values[8] of Q ($\approx 10^8$) and E_{ax} (2MV/m), adequate for a linear accelerator. We have shown that this stability lasts over long time periods under more than "full power". Moreover, exposure to air, such as might occur in an accidental accelerator leak, would not be a disaster, since the resonator has been shown to keep its properties without retreatment of its surface. We have shown, in fact, that quite long exposures to air are not harmful. In addition, this work demonstrates that considerable thermal cycling from liquid helium to room temperature causes no deterioration.

In future work we shall examine the radiation damage effect of massive x-ray doses and the effect of heavy-ion bombardment. Work is in progress to examine the Nb_2O_5 layer and methods of optimizing it. Several methods are being developed for correctly phasing successive resonators in the presence of mechanical vibration.

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[4] E_{ax}, the axial electric field, is the equivalent traveling wave value, or field available for acceleration; all other fields are standing-wave values. E_{ax} refers to the actual short (one $\lambda/2$ section) helix resonator used here. In an accelerator design, long helix (number of $\lambda/2$ sections) resonators would be used. For such, with the same E_{max} and B_{max} as observed in this experiment, E_{ax} values quoted would be increased by a factor of ~1.2.

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